Lessons Learnt from the Optical Communications Demonstrator (OCD)

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ABSTRACT

The Optical Communications Demonstrator (OCD) is a laboratory based lasercom terminal that was developed to validate several key technologies such as precision beam pointing, high bandwidth beacon tracking and beacon acquisition. The unique architecture of OCD uses a single focal plane array (FPA) and a single fine steering mirror (FSM) for beacon acquisition, beacon tracking and point-ahead compensation. A fiber-coupled laser transmitter further reduces the complexity of the terminal. Over the last year, system level integration, test and characterization of the terminal were conducted. Here we present results from the integration and test (I&T) of the terminal with the Lasercom Terminal Evaluation Station (LTES), with particular emphasis on the fine tracking performance. Furthermore, we will describe lessons learnt from the implementation and testing of OCD that are relevant to the design of future flight optical communication terminals. The completed OCD is now being used in a series of ground-ground experiments to understand atmospheric effects and to gain experience operating the OCD.

Keywords: Optical Communications, Laser Communications, Beacon Acquisition, Tracking, Free-space, LEO, GEO, OCD

1. INTRODUCTION

The greatest advantage of laser communications over RF for space-to-ground communications, namely narrow beamwidth, also poses the most technical challenge. The considerably smaller transmit beamwidth, typically on the order of tens of microradians, imposes stringent demands on the pointing system in the presence of spacecraft vibration. Inaccurate beam pointing can result in significant signal fades at the receiving site resulting in a large number of burst errors. Thus, one of the important steps in realizing space-ground laser communications is to track the target (or receiver) with residual pointing error that is small compared to the transmit beamwidth.

The Optical Communications Demonstrator (OCD) program at the Jet Propulsion Laboratory (JPL) was created to demonstrate in a laboratory environment several key free-space lasercomm technologies, primarily precision beam pointing, high bandwidth tracking and beacon acquisition. The OCD terminal, designed and constructed over the last few years, uses a reduced complexity architecture. In this patented architecture, only one fast steering mirror (FSM) and one detector or focal plane array (FPA) are used for all acquisition, tracking and point-ahead functions [1]. A large field-of-view (FOV) array detector is used in a "windowed" mode for achieving high frame rates that are required in the tracking mode. Since OCD was designed to show how data can be dumped from LEO/GEO orbit to ground at very high rates (100 Mbps to several Gbps), there is no communications detector on the terminal. No redundant components exist in the OCD terminal further simplifying the lab model.

Numerous papers describing the OCD design, construction, assembly and integration were published over the last few years [2,3]. In this paper, we present the latest results from OCD performance measurements, particularly the characterization of the fine tracking function. We begin, in Section 2, with a brief description of OCD including its optics, opto-mechanics, electronics and software. In the following section we present recent results on fine tracking loop bandwidth and algorithm accuracy. Then we describe lessons learnt from building and testing the OCD that we believe will help us build a better optical comm terminal in the future. Finally, we discuss how OCD is being used to understand link performance in the presence of atmosphere.

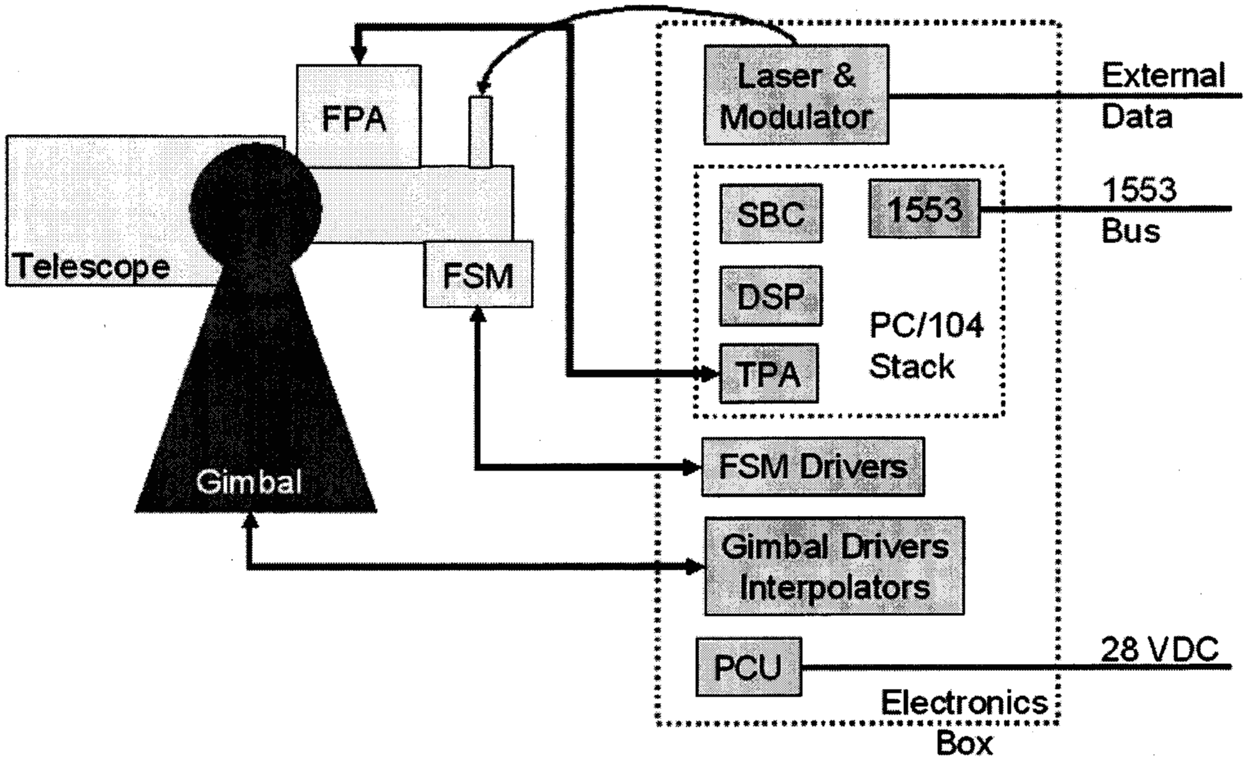

Figure 1. Block diagram of OCD showing the major components and interfaces between them. FPA: Focal Plane Array; FSM: Fine Steering Mirror; SBC: Single Board Computer; 1553: MIL-STD-1553B interface card; DSP: Digital Signal Processor board; TPA: Tracking Processor Assembly; and PCU: Power Converter Unit.

2. OCD DESCRIPTION

The OCD consists of several components - the telescope optics assembly (TOA), a gimbal for coarse pointing, a fiber-coupled laser transmitter, and electronics to control and operate the terminal. The TOA is mounted on an azimuth/elevation (Az/El) gimbal, and the laser and electronics are packaged into an "electronics box" as shown in Fig. 1 and Fig. 2. The TOA consists of a 10-cm telescope, a CCD array detector, a two-axis fine steering mirror, and miscellaneous opto-mechanical components to channel the light appropriately. The OCD optical assembly has three paths: a transmit channel that relays light from the fiber-output, off the FSM and out of the telescope aperture; a receive channel to relay the incoming beacon to the CCD; and a boresight channel to divert part of the transmit signal to the CCD [4,5]. Since the receive path is not deflected by the FSM, the beacon spot on the CCD moves around due to spacecraft jitter. The function of the electronics is to point the beam by controlling the FSM so that the transmit laser spot (from the boresight channel) on the CCD maintains a given vector distance from the beacon spot. The transmit laser is located away from the telescope, and is coupled to the TOA using a single mode optical fiber. The fiber coupled laser transmitter eases thermal management issues, and makes it easy to put in a different laser.

Though some of the electronics for the CCD are mounted on the TOA itself, most of the electronics (including the processor) are placed away from the TOA and gimbal. The acquisition and tracking (acq/trk for short) electronics for the OCD consist primarily of a Texas Instruments TMS320C40 (C40 for short) based DSP card and a Tracking Processor Assembly (TPA) card set. The C40 DSP card provides local data processing of camera images, and control of the fine steering mirror (FSM) and gimbal. The TPA is a custom built card set used to interface the C40 card to the CCD, FSM, gimbal and laser. The C40 card communicates with the TPA cards through a high-speed Global Bus. A 486/586 processor based single board computer (SBC) is the main instrument controller which is expected to accept commands from and send status information to the bus controller (BC) through the MIL-STD-1553B card. The C44 (a faster, surface-mount version of the C40) DSP card is slave to the x86 SBC and performs all the

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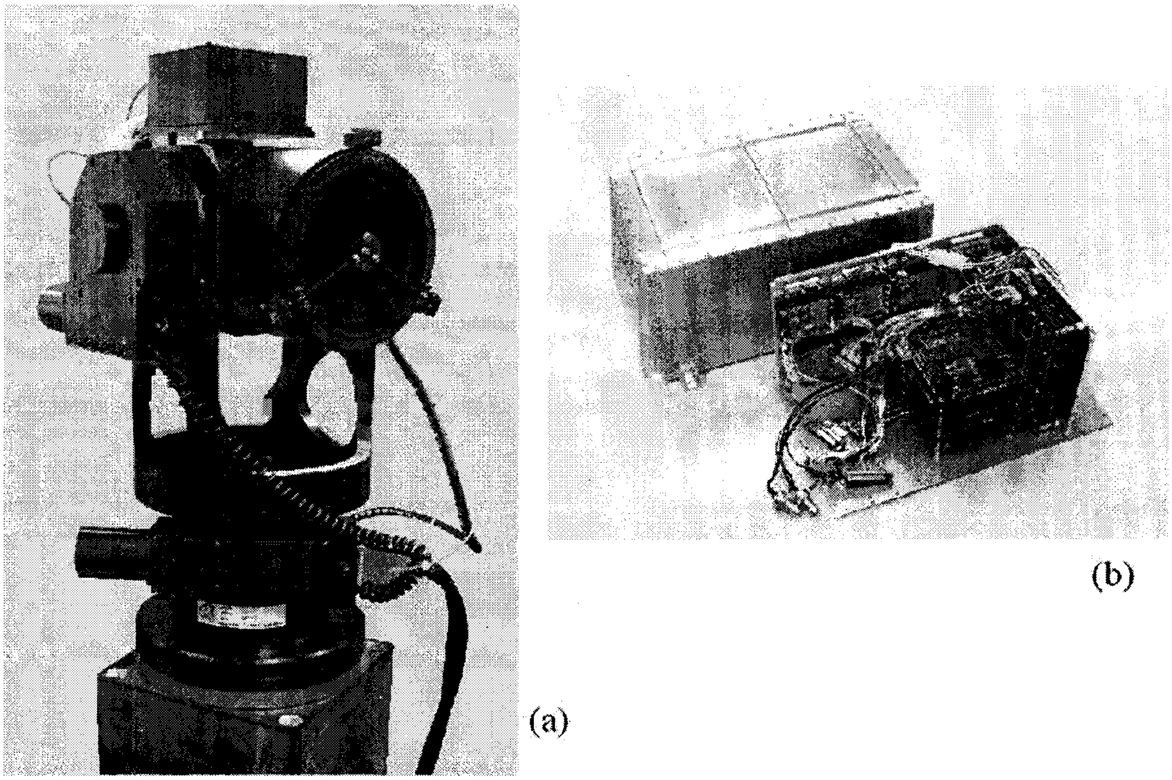

Figure 2. Photographs of the fully assembled OCD hardware: a) Telescope Optics Assembly (TOA) mounted on gimbal; and b) electronics box. The TOA and gimbal together measures about 1.5' high and 1' in diameter. The electronics box contains control electronics, DC-DC converters, FSM and gimbal drivers, gimbal interpolators and laser (not shown above). The electronics enclosure is 12 in x 8 in x 6 in.

acquisition and tracking related processing. The host SBC, slave DSP card, TPA card set and 1553 cards were all procured/fabricated in PC/104 form factor and stacked to form a 4" cube controller [6–8].

During acquisition of the beacon, the control software scans the 128x128 CCD camera image to locate the beacon position in the CCD field of view. The gimbal may have to be moved during this phase if the CCD FOV is smaller than the target uncertainty space. A valid beacon is defined as one or more pixels having a value greater than a predefined threshold. During the acquisition process, the transmit laser is turned off and the FSM is held fixed so as not to confuse the acquisition algorithm. Once a valid beacon is found the software then enters the tracking mode and the transmit laser is turned on. During tracking, a centroiding routine provides sub-pixel x- and y-coordinate information on the location of the beacon and transmit laser positions in the CCD field of view. This information is used to control the FSM and gimbal as well as adjust the location of active windows to be scanned on the next pass. During tracking, the CCD dumps all pixel values except those from two 8x8 windows around the laser and beacon spot to achieve a frame rate of 2 kHz. The function of the tracking routine is to maintain the transmit beam at a fixed position relative to the beacon using the FSM and to keep the transmit beam in the center of the CCD using the gimbal.

The TOA, gimbal, laser, control electronics and software were all individually tested and integrated several months ago. The fully assembled OCD weighed 21 kg and consumed approximately 50 W when the gimbal was powered up, but not moving. The gimbal alone can consume up to 80 W if both elevation and azimuth axes are moving rapidly. Under these conditions, OCD will consume about 130 W of power. Table 1 shows the mass and power breakdown between various components.

The fully assembled OCD was co-aligned with the Lasercomm Test and Evaluation System (LTES) for test and characterization. LTES was built at JPL as a general purpose diagnostic tool to test any optical communication terminal with aperture up to 8 inches in diameter [9,10]. LTES provides a beacon to the terminal under test and measures the properties of the transmitted signal beam. Some results of the optical characterization of the OCD,

Table 1. Mass and power consumption numbers for different components of the OCD

Item	Notes	Mass	Power
TOA	Includes telescope, optics, mounts CCD and FSM	5.6 kg	-
Gimbal	Worm-gear-drive Az/El gimbal from Automated Precision Inc. (API)	10.0 kg	80 W
Laser	SDL laser with Hytec modulator 30 mW ave power and 500 Mbps	0.7 kg	5 W
Electronics Box	Includes PC/104 stack, DC-DC converters, FSM and gimbal drivers, gimbal interpolators and enclosure	4.7 kg	45 W
	Total	**21.0 kg**	**Ave. 50 W** Peak. 130 W

including efficiency of various channels can be found in Ref. [6]. The focus of this paper is to present characterization of the OCD fine tracking performance.

3. FINE TRACKING PERFORMANCE

In an optical communication link, a part of the link budget must be reserved for mispointing. Based on static mispoint error and rms tracking jitter, one can determine the probability that the pointing-induced fades are above the allocated reserve. These larger-than-allowance fades cause burst errors in the link. Static mispoint error can be caused by optics misalignment or by poor knowledge of parameters needed to compute point-ahead angle. The tracking performance depends on a) the centroiding accuracy of the beacon and transmit laser spots and b) the uncompensated (or residual) vibration from both the platform and gimbal. In practice, the mispointing allowance is limited by the dynamic range of the receiver and the jitter compensation is limited by available technology. The following analysis and characterization of OCD's tracking performance gives the link designer information needed to make trade-offs between pointing allowance and tracking jitter.

With the OCD assembled and integrated, we characterized its tracking performance. A detailed characterization of the fine-tracking control loop was done by Racho, *et. al.* [11]. The control loop consists of a) a DALSA 128x128 CCD camera which records the images of the beacon and laser spots; b) a DSP processor which determines where the laser spot should be; and c) a fine steering mirror (FSM) which steers the transmit beam to the desired location. All of the above functions are performed every 500 μsec or at a 2 kHz rate. Results of the characterization is summarized in Figure 3 which shows the vibration compensation in dB as a function of frequency. As is clear from the figure, the 0-dB bandwidth of vibration compensation was greater than 50 Hz in both axes. The 3-dB closed loop bandwidth (traditional quantity of interest) was over 110 Hz in both axes. The vibration compensation is more relevant here as it measures instantaneous error and shows to what level input disturbances are compensated. For example, a disturbance of 10 μrad at 1 Hz would be suppressed by 17 dB resulting in an uncompensated jitter of 0.2 μrad. The control loop slightly amplifies disturbances near 100 Hz but leaves uncompensated anything above a few hundred Hz. The residual rms jitter, of course, depends on the platform vibration spectrum. In fact the residual angular jitter is given by [12]:

$$\theta_{\text{rms}} = \sqrt{\int_0^\infty S(f)|R(f)|^2 \, df}$$

where $R(f)$ is the vibration compensation function, shown in Figure 3, and $S(f)$ is the power spectral density of the TOA vibration. Thus, the tracking bandwidth requirements can be relaxed for compact next generation spacecrafts that are "quite".

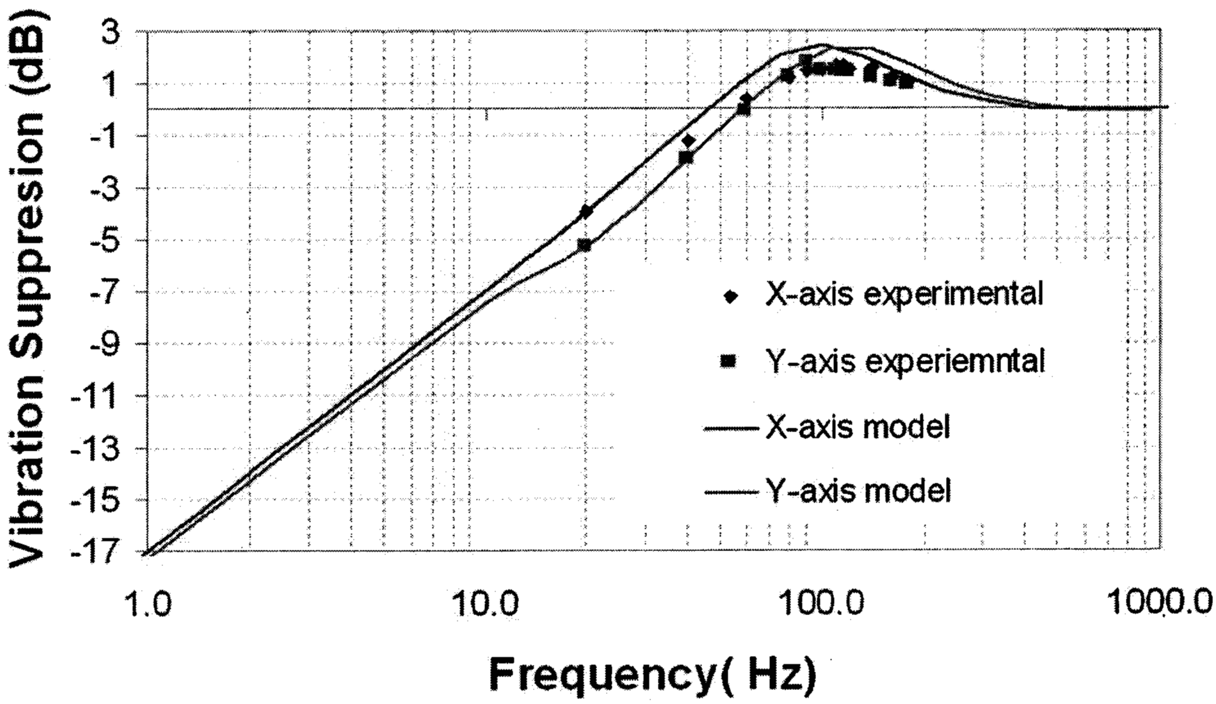

Figure 3. Vibration compensation of OCD's fine tracking loop. The markers are experimental data and the solid lines are based on an analytical model. The responses in both axes are quite similar.

The second contribution to jitter is the centroiding accuracy which depends on such factors as signal strength; FPA dark and readout noises; ADC resolution; pixel-pixel non-uniformity or quantum efficiency variations; and quality of imaged spots. The centroiding accuracy for the laser or reference spot will be better than the beacon spot because the reference spot is generated and controlled within the terminal. The beacon, however, has to traverse the atmosphere and thus can fluctuate substantially.

The diffraction limited spot-size (Airy disc) of the focused beacon and refernce beams on the CCD is approximately 3-by-3 pixels. Because of the "peaked" nature of the Airy pattern, a substantial portion of the incident light can be concentrated on just one pixel. Though CCDs have very low pixel-pixel and intra-pixel non-uniformity, they are quite noisy at the high frame-rate readout necessary for tracking. The DALSA CCD, used in the OCD, has less than 5-bit effective resolution in the tracking or fast frame readout mode. Analysis and simulation with the preceeding information show that one-tenth of a pixel accuracy can be obtained when the brightest pixel is about half the saturation value [13].

Figure 4 shows the experimentally measured PDF of the centroiding error for the beacon and reference spots. The standard deviation in each axis is approximately one-tenth of a pixel for both spots. Since each pixel is mapped to 10 μrad in the object space, the centroiding accuracy is about one μrad. The beacon error is slightly larger because of vibration between OCD (mounted on a tripod) and LTES (on a separate optical table). These numbers are consistent with the simulation results described earlier. We also measured the OCD transmit beam jitter using the Lasercom Test and Evaluation Station (LTES). As mentioned earlier, The OCD was placed on a tripod and the light was coupled into LTES through a set of two large mirrors. With the tracking turned off, the jitter observed on LTES is primarily because of vibration of the the tripod, coupling mirrors and LTES, and atmospheric effects. With the tracking turned on, the jitter increases slightly to about 1.7 μrad in each axis. Since the reference and beacon centroid errors are both approximately 1 μrad, we expect the net jitter to be the root-sum-square (RSS) of the two values or about 1.4 μrad. Though no intentional OCD or beacon vibration was introduced, prevailing vibration between the OCD and LTES is believed to be the source of the discrepancy.

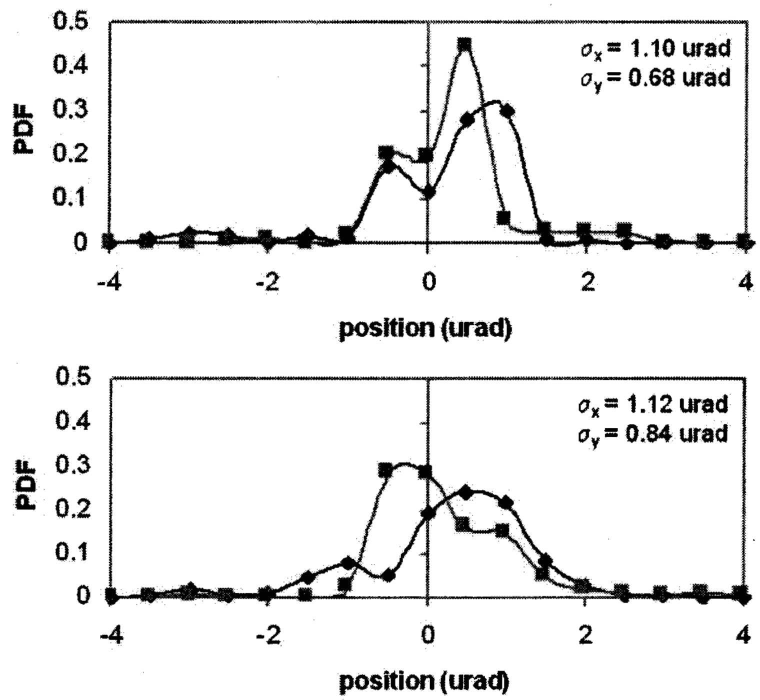

Figure 4. Centroiding accuracy of OCD a) laser/reference spot; and b) beacon spot. Centroid data was obtained from the OCD CCD at 2 kHz for a 2-second interval. The standard deviations of the centroid errors were about 1 μrad for both beacon and laser and in both axes.

4. LESSONS LEARNT FROM OCD

Lab tests and characterization of OCD clearly demonstrate that the OCD architecture works. Acquisition, fine tracking and point-ahead functions can all indeed be achieved with just one focal plane array and one fine steering mirror. The outdated components in OCD, however, limited the 0-dB vibration compensation bandwidth to 50 Hz. The OCD FSM is a General Scanning beam steerer with a first resonance at 18 Hz and is no longer available from the manufacturer. Also, to enable CCD sub-frames to be read at 2 kHz, rows and columns of CCD data had to be dropped until the region-of-interest (ROI) is reached which adds to the loop delay. Newer FSMs and FPAs will substantially improve the bandwidth and therefore will enable compensation of higher frequency jitter. We are currently testing FSMs from Left Hand Designs which have a bandwidth of greater than 300 Hz. We are also investigating Active Pixel Sensors (APS), newer CCDs with simultaneous multiple channel readout and hybrid CCDs to improve performance by reducing the loop delay.

The second key feature of the OCD architecture is the fiber coupled laser. Fiber coupled lasers provide a simple interface between the laser and the telescope optics assembly which makes changing lasers easy. Separation of the laser from the TOA also makes thermal management simpler as one need not worry as much about the impact of heat from the laser on the TOA. Finally, removal of the laser/modulator from the TOA reduces the mass/inertia that the gimbal has to move which relaxes gimbal requirements. Except when extremely high peak powers are needed, as for deep space missions, fiber coupled laser appears to be the ideal choice.

The OCD coarse pointing mechanism is a low cost worm-drive gimbal from Automated Precision Inc. (API). Several factors such as a) gimbal fork vibration; b) position-dependent friction; and c) slight offset of moment of inertia (MOI) from the pivot point made it difficult to implement a stable control algorithm and prevented us from successfully implementing coarse tracking. We are further investigating the gimbal to understand the origin of the problems so that we can properly specify gimbal requirements for future missions.

Furthermore, in working with OCD in the lab we found that it would be beneficial to have better accessibility and control of alignment mechanisms. For example, we found it difficult to align the nominal reference spot on the

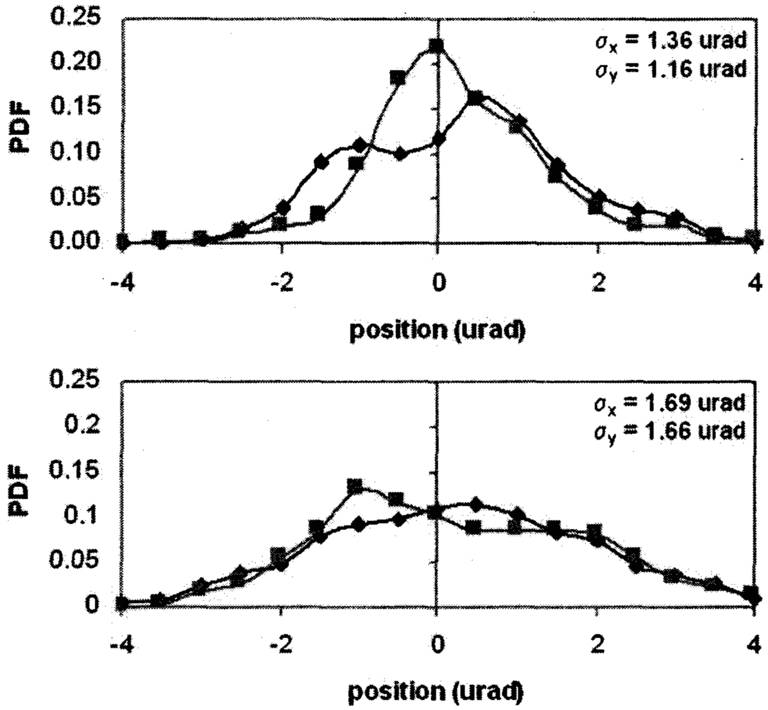

Figure 5. OCD transmit beam jitter as measured in the LTES acquisition channel a) with OCD tracking turned off and b) with OCD tracking turned on. The data was acquired over a 4-second interval and sampled at 1 kHz.

FPA to the desired position using shims. As a final note, we emphasize that the OCD was built for lab use only. Most, if not all, of the components are COTS and require environment testing for use in space. Significant software work is required to interface OCD to a host spacecraft and to add diagnostic and self-test capabilities.

5. SUMMARY

We have completed design, construction, assembly, integration and test of the OCD in lab which have demonstrated that the OCD architecture works. Acquisition, fine-tracking and point-ahead functions were all accomplished with just one fine steering mirror and one focal plane array. In fact, the fine tracking loop had a 0-dB vibration compensation bandwidth of over 50 Hz and centroiding accuracy of 1 μrad. Research is underway at the component level to improve control loop performance.

The OCD is currently being used in ground-ground optical link experiments, primarily to understand the impact of atmospheric effects on tracking [14]. In these experiments, the OCD is placed at Strawberry Peak (near Lake Arrowhead, CA) and tracks a beacon from Table Mountain Facility or TMF (near Wrightwood, CA) located 45 miles away. The modulated signal from OCD is then received at TMF using a 24-in telescope. We plan to augment the field experiments with more controlled experiments in the lab by simulating atmospheric effects. The effects of atmosphere-induced beam-wander and scintillation can be simulated in LTES by varying beacon intensity and by distorting beacon phase using phase-screens. The goal of these experiments are to understand how fluctuations in beacon intensity and beacon angle-of-arrival affects OCD tracking, and how that translates to burst errors at the receiver.

We are currently funded to build an optical communication terminal for the International Space Station Engineering Research and Technology (ISSERT) program. This terminal is based on the OCD architecture but has increased performance and functionality [15]. Lessons learnt from the OCD are being applied to this next generation optical communication terminal which will be used to demonstrate greater than 1 Gbps optical link from LEO to ground.

ACKNOWLEDGMENTS

The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the work of N. Page, B. Sanni, G. Ortiz, J. Lesh and T.-Y. Yan.

REFERENCES

1. J. Lesh, C.-C. Chen, and H. Ansari, "Lasercom system architecture with reduced complexity." U.S. Patent Number 5,517,016, May 1996.
2. C.-C. Chen and J. R. Lesh, "Overview of the Optical Communications Demonstrator," *SPIE Proceedings - Free-space Laser Communications Technologies VI* **2123**, pp. 85–94, 1994.
3. T.-Y. Yan, M. Jeganathan, and J. R. Lesh, "Progress on the development of the Optical Communications Demonstrator," *SPIE Proceedings* **2990**, pp. 94–101, 1997.
4. N. A. Page, "Design of Optical Communications Demonstrator instrument optical system," *SPIE Proceedings - Free-space Laser Communications Technologies VI* **2123**, pp. 498–504, 1994.
5. B. R. von Lossberg, "Mecahnical design and design processes for the telescope optical assembly of the Optical Communications Demonstrator," *SPIE Proceedings - Free-space Laser Communications Technologies VI* **2123**, pp. 505–517, 1994.
6. M. Jeganathan and S. Monacos, "Performance analysis and electronics packaging of the Optical Communications Demonstrator (OCD)," *SPIE Proceedings* **3266**, pp. 33–41, 1998.
7. PC/104 Consortium, Mountain View, CA., "The PC/104 Specification."
8. IEEE Standards Office, Piscataway, NJ, "The IEEE-P996 Specification."
9. K. E. Wilson, N. A. Page, A. Biswas, H. Hemmati, K. Masters, D. Erickson, and J. R. Lesh, "Lasercom Test and Evaluation Station for flight-terminal evaluation," *SPIE Proceedings* **2990**, pp. 152–8, 1997.
10. A. Biswas, K. E. Wilson, and N. A. Page, "Lasercom Test and Evaluation Station (LTES) development: an update," *SPIE Proceedings* **3266**, 1998.
11. C. Racho and A. Portillo, "Characterization and design of digital pointing subsystem for Optical Communications Demonstrator (OCD)," *SPIE Proceedings* **3615**, 1999.
12. E. A. Swanson and J. K. Roberge, "Design considerations and experimental results for direct-detection spatial tracking systems," *Optical Engineering* **28**, pp. 659–666, 1989.
13. S. Lee, J. Alexander, M. Jeganathan, and J. Lesh, "Pointing and tracking subsystem design for optical communications link between the International Space Station and ground," To be published.
14. A. Biswas, J. Ceniceros, M. Novak, M. Jeganathan, D. Erickson, J. D. Pew, B. Sanii, A. Portillo, V. Lo, and J. Lesh, "45-km horizontal path optical link experiment," *SPIE Proceedings* **3615**, 1999.
15. J. Sandusky, M. Jeganathan, G. Ortiz, A. Biswas, S. Lee, G. Parker, B. Liu, D. Johnson, and J. Lesh, "Overview of the preliminary design of the optical communication demonstration and high-rate link facility," *SPIE Proceedings* **3615**, 1999.